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The SLR data pertaining to the anomalous motions of Quincy, Simosato and Huahine have been written up for publication and have been submitted. A copy of this paper is included with this semi-annual progress report (Satellite Laser Ranging and Geological Constraints on Plate Motion, by C. G. A. Harrison and Nancy Browning Douglas). We have also submitted an abstract for presentation at the Western Annual Meeting of the Amewrican Geophysical Union, which is also included with this report (SLR Results and Non-Rigid Plate Motions, by C. G. A. Harrison and Nancy B. Douglas).

In order to follow up on some of the results which are described in this paper, we have started analysing SLR data from other stations located close to subduction zones. We eventually hope to be able to test the hypothesis of Otsuki (Tectonophysics, 159, 73 - 94, 1989) who has suggested a model in which the amount and direction of strain in the back arc area is related to the absolute velocities of the subducting and overriding plates. In order to do this we shall also analyse VLBI data from appropriate locations, in order to expand our coverage of subduction regions.

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Satellite Laser Ranging and Geological Constraints on Plate Motion

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Abstract

We have analysed Satellite Laser Ranging observed baseline rates of change and compared them with rates predicted by plate motions as determined from sea floor spreading rates and directions. With the number of years of observation now over six for many of the baselines, the inaccuracy of determining baseline rates of change has diminished so that in some cases it is less than a few mm per year. Thus, the geological rates can now be compared directly with measurements which sometimes approach these geological rates in accuracy. In most cases, there is good agreement between the rates determined from SLR and geology, but in some cases there appear to be discrepancies. These discrepancies involve many of the data for which one end of the baseline is either Quincy (California), Huahine (French Polynesia) or Simosato (Japan). We have devised a method for looking at the discrepancies for these SLR observatories which allows us to calculate the motion not modelled by the geologic information. The results will be discussed in terms of what is known about plate margins, and other information.

Introduction

Satellite Laser Ranging (SLR) to the Lageos satellite has been in operation for over a decade. The accuracy of determining baseline lengths between

SLR observatories has been improved to the point where rates of change between sites can be measured to a few mm per year (Christodoulidis et al., (1985); Tapley et al., (1985)). It has therefore become possible to compare in a meaningful way rates of change established from SLR data and rates of change established from geological considerations. In this paper we compare these two methods in order to arrive at some information about whether geological rates, which are established for time spans of a few million years, are comparable to rates established from a few years of SLR data.

In order to compare the two sets of results we have used several different models which describe the geological rates. In particular we have used the models developed by Minster and Jordan (1978) and Chase (1978) and a more recent one calculated by DeMets et al. (1989). The data which go into these models consist of three types. Sea floor spreading rate information gives rates of separation between two plates separated by a mid-oceanic ridge which are calculated by measuring the distance between characteristic marine magnetic anomalies whose age is known from the magnetic field reversal time scale. The characteristic anomalies are usually less than three million years old, so that these rates are average rates over this time scale.

A second type of information consists of the strike of fracture zones offsetting the mid-ocean ridge system. This information gives the direction of relative motion between the plates separated by the mid-ocean ridge. Again, the information gives an average direction over the last few million years. If the direction of motion changes then it will take some finite amount of time for the strike of the fracture zone to respond to this directional change.

The third type of motion indicator comes from earthquakes, and consists of calculating the directions of first motion from large earthquakes. This also gives information about relative directions, but since the earthquakes may be on subduction zones as well as on spreading centers, valuable additional information is provided. However, the information is restricted to present day relative plate velocities.

Earlier work has been described by Christodoulidis et al. (1985) and Tapley et al. (1985). Christodoulidis et al. (1985) showed that overall there was good agreement between SLR results and those from geologic information. They calculated 34 interstation baseline rates of change between 12 different SLR stations, using the SL-5.1 results from 1979 to 1982. The average uncertainty in the SLR rates from this limited data set was about 2 cm/yr. They then compared these rates with those predicted by Minster and Jordan (1978). Overall the results were comparable, in that the correlation coefficient between the SLR rates and the Minster and Jordan rates was 0.61. However, in some cases there were discrepancies of up to 2 cm/yr. These may have been caused by the inaccuracy of determining SLR rates from the limited data available.

In this paper we discuss a set of SLR rates measured over a much longer time interval, resulting in lower errors for these rates, and compare them with rates from a number of plate tectonic models. We find that most of the SLR data fit the plate tectonic models to within the formal uncertainties, but that in some cases (involving a small number of stations) there is a significant discrepancy. These stations are Quincy (northern California), Huahine (French Polynesia) and Simosato (Japan).

A very similar data set has been analysed by Smith et al. (1989) using a different procedure. Many of the results which they obtain are simlar to those described in this paper.

Methods of SLR Data Analysis

We have used for the most part the data set of annual station positions derived from the GSFC SL7.1 method of SLR analysis (Smith et al., 1989) for data from launch through the end of 1986. This data set A is the data described in tables 2, 3 and 4. A more thorough treatment of these data is found in Douglas (1988). A more recent data set (data set B) was used to estimate motions of the three stations mentioned above, since we wished

wished to use the most recent data in order to achieve a better statistical estimate of uncertainty. This is the data set used to generate the information in tables 5, 6 and 7 and in all of the figures. It consists of geodesic rates based on quarterly station positions through June of 1988. We have used the geodesic rate changes, i.e. the temporal changes in the length of arc along the ellipsoid of revolution between the two stations under consideration. For the geologically derived rates, this change may be calculated from relative rotation pole positions and rates given in the plate tectonic models. It is given by the following equation.

$$\frac{d\lambda}{dt} = \frac{R \sin\theta_1 \sin\theta_2 \sin\alpha}{\sqrt{1 - (\cos\theta_1 \cos\theta_2 + \sin\theta_1 \sin\theta_2 \cos\alpha)^2}} \frac{d\alpha}{dt} \tag{1}$$

where the quantities are identified in figure 1. The z axis is drawn through the rotation pole for the relative motion of plate 1 (on which station P1 is situated) and plate 2 (on which station P2 is situated). $d\alpha/dt$ is the rotation rate and R is the radius of the Earth. The SLR rates of change were calculated using a weighted least squares procedure, resulting in a change plus a standard error for this change. Both these quantities will be used in the method to determine additional motions described below. Our data set A includes rates derived from Goddard Space Flight Center (GSFC) SL7.1 solution for laser tracking data through the end of 1986. In our analysis used the subset of twenth stations with at least four years of tracking data, shown in table 1. Between these stations we computed 134 baseline rates, for all station pairs with four or more common tracking years (rather than the 308 possible baseline rates). A more complete description of the results is given in Douglas (1988). For these 134 baseline pairs the average of all the standard errors of the rates was 17 mm/yr. A complete list of the baseline rates plus standard errors, and the estimated rate from Minster and Jordan (1978), DeMets et al. (1989) and Chase (1978) can be obtained from the senior author.

In terms of the agreement between the SLR rates and the plate tectonic rates, some comparisons are summarised in tables 2 and 3. Table 2 gives correlation coefficients and slopes for the Minster and Jordan versus the SLR rates as the dependent variable, for all SLR rates using more than four years of data. It can be seen that in general as the data with larger uncertainties are omitted from the calculation the agreement becomes better. Also the agreement as measured by the correlation coefficient is considerably better than that reported by Christodoulidis et al. (1985). Table 3 shows a similar comparison for SLR rates established using more than five years of data. There is a slightly higher correlation coefficient for the Nuvel model (DeMets et al., 1989) than for the other two, but the difference is not statistically significant. Also, the correlation coefficients are better for the 5 + years of data than for the 4 + years of data shown in table 2.

These tables also show that the correlations are better if the intra-plate numbers are omitted from the calculation. This is probably due to the fact that these intraplate numbers tend to be dominated by non-rigid plate behaviour close to the plate boundaries. For the data set with the best agreement between SLR and plate tectonic rates (the Nuvel model using 5 + years of data and only interplate baselines) the maximum discrepancy is 2 cm/yr.

The discussion above shows that there is in general very good agreement between the SLR rates and the plate tectonic rates, with a slight preference for the latest plate tectonic model produced by DeMets et al. (1989). However, there are some significant discrepancies which we shall now discuss.

SLR and Plate Tectonic Discrepancies

It was noticed early on in this analysis that several stations seemed to have a greater degree of discrepancy between SLR rates and plate tectonic rates. In order to quantify this in a more systematic way, we have calculated the following quantities for each station. We measured the ratio between the discrepancy and the standard error of the SLR rate. High values reflect a larger uncertainty normalised to the potential error in the SLR data. Then these values were averaged for each station. Results are given in table 4, for each station with 6 or more rates. The stations with the two largest numbers, Owens Valley and Grasse, have one very large ratio (between these two stations) which distorts the generally good agreement between SLR and plate tectonic rates. The SLR rate between these stations is -98 ± 8 mm/yr and the Minster and Jordan rate is 20 mm/yr, giving a ratio of 14.8.

The next largest value comes from Huahine, indicating that there may be some additional plate motion for this station. The high value for Monument Peak is also caused by a single large value, from Fort Davis, as is the high value from Otay Mountain (from Quincy). Although these two stations may be recording non-rigid plate motions, we have not considered them further because there are several other stations which have more discrepant values. For instance Quincy has a relatively high value, caused by many disagreements between SLR and plate tectonic rates, as does Simosato.

Bear Lake also shows a high degree of discrepancy. However, for Bear Lake there are only five baselines excluding the baseline to Quincy and so we have not analysed the Bear Lake data any further.

Figure 2 shows the data for Quincy. Each line shows the direction towards one of the other SLR stations for which there are useable baseline data to Quincy. By each line there is a number which gives the discrepancy between the SLR data and the Minster and Jordan model, such that positive values show that the SLR baseline rate is more positive than that given by Minster and Jordan. In other words, positive values indicate that the station pair is moving apart, compared with the Minster and Jordan (1972) prediction. The number in parentheses is the standard error in determining the SLR baseline rate change. For all practical purposes, the formal errors in the Minster and Jordan model are so much smaller than the SLR errors that we have ignored them. We wish to choose an additional motion of Quincy so that the discrepancy is minimised. We have done this in a weighted least squares sense, described below.

The bearings from the stations under consideration to the other stations are $\phi_1, \phi_2, \cdots \phi_n$. The unmodelled velocities (SLR - Minster Jordan) are $v_1, v_2, \cdots v_n$, each of which has an error $e_1, e_2, \cdots e_n$. In order to determine the additional motion of S we minimize

$$F = \sum_{i=1}^{n} \left(\frac{v_i - X\cos\phi_i - Y\sin\phi_i}{e_i}\right)^2 \qquad (2)$$

where X, Y are the N, E, components of the velocity.

$$\frac{\partial F}{\partial X} = 0 \qquad (3)$$

$$\frac{\partial F}{\partial Y} = 0 \tag{4}$$

Equations 3 and 4 may be solved for X and Y.

The result is shown in figure 2, and it can be seen that the additional unmodeled motion of the Quincy station is towards the NNW at 22 mm/yr. We have also analysed the errors and have determined an oval of confidence around the motion vector. This has been done in the following way.

We find the variance - covariance matrix W, where

$$W = \begin{pmatrix} \sigma_x^2 & \sigma_{xy}^2 \\ \sigma_{xy}^2 & \sigma_y^2 \end{pmatrix} \tag{5}$$

$$W = (A^T V^{-1} A)^{-1} \tag{6}$$

where

$$A = \begin{pmatrix} \cos\phi_1 & \sin\phi_1 \\ \cos\phi_2 & \sin\phi_2 \\ \vdots & \vdots \\ \cos\phi_n & \sin\phi_n \end{pmatrix} \tag{7}$$

and

$$V = \begin{pmatrix} e_1^2 & 0 & \cdots & 0 \\ 0 & e_2^2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & e_n^2 \end{pmatrix} \tag{8}$$

W is then rotated to remove the diagonal elements

$$W' = \begin{pmatrix} \sigma_{x'}^2 & 0 \\ 0 & \sigma_{y'}^2 \end{pmatrix} \tag{9}$$

and $\sigma_{x'}$, $\sigma_{y'}$ used to construct an oval of confidence around the motion vector.

The formal error for this additional motion of Quincy with respect to the North American plate is less than 2 mm/yr. There is general agreement between the data coming from different areas. For instance the data coming from the SE quadrant all show added extension in that direction. Data coming from the east show a small amount of extension except for one fairly inaccurate result which will not be weighted very much in the calculation. Data coming from the NE show very consistent small amounts of closure, whereas data from the western side are all consistently fairly small.

It is clear that this error analysis leaves something to be desired. The error analysis does not take into account any scatter or disagreement between the original results and the proposed motion. And it is fairly clear that in many cases the formal errors do not account for the actual errors in the data. This means that there probably are systematic errors in these SLR data which do not show up on the distance versus time plots. This can be most easily seen in the data from Quincy (figure 2). We can compare the observed data with what the model produces, which has been done in table 5. The fact that the ratio of the disagreement between SLR and geological rates and the formal standard errors is frequently very large (last column in table 5) shows that the formal standard errors are probably too small.

We have therefore carried out an alternative analysis of errors. We have calculated the best fitting additional motion vector using unweighted values. We have then compared the individual station results with those predicted by this additional motion vector and used the differences to establish a standard deviation of each individual result. This is then used as a constant error value for the analysis outlined above.

Results for both methods are given in table 6. In this table, it can be seen that the final error for the Quincy data is now much larger than when the formal standard errors are used. Consequently, we have used this second result (labelled (b) in table 6) for comparison with other data. The difference between the (a) and (b) results for the other stations is in general quite small. There is often a large discrepancy in the bearing of the X - axis for the error ellipse, but since the difference between the X and Y axes for these ellipses is in general quite small, this discrepancy is not important. The only station other than Quincy which shows a significant difference between the two methods of analysis is Huahine. For this station, the (b) result gives much smaller errors than the (a) result, although the alignment of the error ellipse, which is quite elongated in both cases due to the placement of the data, is similar. In order to take the more cautious approach we have used the (a) result from Huahine in further discussion.

Quincy Results

Quincy lies on the North American plate (i.e. it is to the east of the San Andreas fault) but it lies west of the Basin and Range extensional area of North America and therefore any movement across the Basin and Range will produce a motion of Quincy relative to cratonic North America. Minster and Jordan [illegible] analysed a variety of data pertinent to this problem, including neotectonic information about strain across the San Andreas fault, plate motions, and Very Long Baseline Interferometry (VLBI) information from stations mainly in North America. They produced three models of motion in which the plate tectonic motion between North America and the Pacific plate was divided up between motion along the San Andreas fault, motion to the west of the fault (California margin) and motion to the east of the fault (Basin and Range). All three models gave approximately the same motion for the Basin and Range extension, of about 9 mm/yr on a bearing of about 55° W. Our results show motion in approximately the same direction but of somewhat larger magnitude.

Having regard for the fairly large errors associated with the SLR data, as shown in figure 3, the discrepancy between the two results is fairly small. It should be noted that the data types used in the two calculations are very different, the VLBI data coming mainly from cratonic North America, whereas the SLR results come from world wide stations.

In addition, some of the seven VLBI results used by Minster and Jordan are to Owens Valley, and another two are to Hat Creek. If there are relative motions between these stations and Quincy, a discrepancy should be produced between Minster and Jordan's results and ours.

The result from Minster and Jordan plotted in figure 3 is their preferred result C which has a 95% error (twice the standard error) of 4.2 mm/yr. Model B of Minster and Jordan is closer in direction to our result and has a 95% error of 7.8 mm/yr, causing the 95% error areas to overlap considerably. We therefore believe that these SLR data confirm that there is an additional motion of Quincy associated with basin and range extension, and agreeing approximately with the results of Minster and Jordan (1987).

Huahine Results

Data from Huahine have also been analysed in a similar manner. Figures 4 and 5 give the results. Because of the geographic location of this station in the southern Pacific ocean, almost all of the baseline directions are towards the NE. The additional motion of Huahine is towards the W at 17 mm/yr. Because of the data locations, the error in the direction of the majority of stations, towards the NE, is fairly low at 3 mm/yr, but the error perpendicular to this direction is very large at 7.4 mm/yr. Nevertheless, the oval of confidence lies very far from the origin, so that the data support an additional motion of Huahine, the directon of which is not very specific. At this time it is difficult to postulate why this additional motion is produced for Huahine. There appears to be little evidence for an additional plate boundary in the Pacific at the present time.

Simosato Results

The third station which gave a significant amount of disagreement was that at Simosato, located in Japan. This station is formally on the Eurasian plate because it is to the west of the trench. But other plates come very close, including the Philippine plate and the North American plate. There is some controversy concerning the location of the plate boundaries in this part of

Japan. Chapman and Solomon (1976) suggested that the North American-Eurasian plate boundary ran through Hokkaido into the trench. However Seno (1985) suggested that the plate boundary might join the trench further south, having run through the Island of Honshu. In a discussion of VLBI data, Heki et al. (1987) suggested that the Japanese VLBI station at Kashima lay on the North American plate. However, Kashima is to the east of Simosato, and from the map (figure 4 in Heki et al. (1987)) it is clear that Simosato is on the Eurasian plate, but very close to both the Philippine and North American plates.

We have therefore done calculations assuming that Simosato is on each of these plates in turn. Results are shown in figures 6 - 11. All of the added motions are roughly towards the NW and are 23 to 37 mm/yr. Because the azimuthal coverage is considerably greater than that for Huahine, the error ellipses are less elongated than in the case of Huahine.

It has been proposed that the collision between India and Asia results in deformation of the Asian continent, the eastern part of Asia moving to the east in order to make room for India. Note that this is not in the right direction to explain the results from Simosato, if this station is truly on the Eurasian plate. The fact that neither of the three results is null suggests that we should look for alternative explanations for the additional motion of Simosato.

The results for Simosato considered to be on the Eurasian plate are in general better in that the reduction in the variance, shown in the last column of figure 5, are larger than for the other two plates, this reflecting mostly the larger motion of Simosato if it is considered to be on this plate (37 mm/yr compared to 23 or 24 mm/yr if it is on the Philippine or North American plates). One possibility is that the strain between the Pacific plate and the three other plates under consideration may not be completely taken up at the trench, and that landward of the trench some of this motion is also seen. In order to check this out we have determined the direction and rate of relative motion between the Pacific plate and the other three plates in the vicinity of Simosato. These results are given in table 7.

There is in fact a remarkable agreement between the directions of the postulated additional motion of Simosato and the direction of relative motion between the Pacific plate and the plates to the west.

Evidence has recently been accumulating that strain across subduction zones is not all taken up within the trench, but that some additional strain occurs landward of the trench axis. This evidence comes from looking at breakouts in holes drilled into the basement by the Ocean Drilling Program (G. Brass, personal communication). These results do not of course give any estimate of the amount of the strain being transferred to the landward plate, but the directions of motion are consistent with the relative motion vectors between the pairs of plates.

Jarrard (1986) has produced a compilation of data relevant to crustal stress behind island arcs. He divided the stress patterns into seven different categories, categories 1 to 3 being extensional, category 4 being indeterminate, and categories 5 to 7 being compressional. The Japan arc was divided into two, at some fairly unclear location. The SW portion of the island arc had a strain pattern behind it in the fifth category, indicating mild compression, whereas the NE portion had a strain pattern in the sixth category, indicating moderately strong compression. These results also agree with our conclusions, although we cannot of course quantify Jarrard's (1986) findings into compressional rates.

Fitch [1972] has also documented occasions where strain is being taken up behind the trench axis, although his discussion centers around transcurrent motion and not normal or reverse motion. Nevertheless, he demonstrates that back arc areas are not simply passive locations, but can be actively involved in strain associated with subduction.

Conclusions

We have shown that overall there is good agreement between SLR rates and those determined geologically. As the number of years of data increases the agreement becomes better. However, for several stations there are significant discrepancies, which have attempted to analyse.

Data from Quincy (in Northern California east of the San Andreas fault) appear to show evidence for Basin and Range extension and our data agree fairly well with those given by Minster and Jordan (1987), having regard for the different data types and origins used in the two analyses. Data provided to us by Goddard Space Flight Center for baselines to Quincy significantly underestimate the error in determining baseline rates of change, as judged by the consistency of the data from different baselines to Quincy. In order to deal with this we adopted a slightly different statistical analysis for Quincy than for the other two stations for which SLR versus geological discrepancies arose.

Data from Huahine (French Polynesia) also showed additional motion unmodelled in the geologic plate motion information. This additional motion may be due to an unknown plate boundary, although this seems unlikely in view of the fact that there is no other information supporting this conclusion. Because of the distribution of baseline azimuths around Huahine, the additional motion is not well constrained in one of its components.

Data from Simosato (Japan) also show discrepancies, which appear no matter whether Simosato is considered to be on the Eurasian, North American or Philippine plates. The additional motion is very closely in the direction of the relative motion between the Pacific plate and the plates on the Asian side of the subduction zone. This suggests that strain may not be completely taken up at the trench axis, but some of it may extend landward of the trench axis. Conventional methods of measuring plate tectonic rates cannot be applied to trenchs, only ridge crests. However, in addition to SLR stations located just behind trench axes, there are also several VLBI stations also located in strategic positions behind island arcs, and so it should be possible to determine how much back arc strain is taking place by looking at the relative motion of these stations with respect to other VLBI stations around the world.

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Table 1

Satellite Laser Ranging Stations Used In This Study

STA	NAME	PLATE	LAT,° N	LONG,° E	LOCATION
7062	OTAY MTN	PCFC	32.6	243.2	SAN DIEGO CA, USA
7082	BEAR LAKE	NOAM	41.9	248.6	UT. USA
7086	FORT DAVIS	NOAM	30.7	256.0	MCDONALD AFB, TX, USA
7090	YARRAGADEE	AUST	-29.0	115.3	AUSTRALIA
7105	GORF STA	NOAM	39.0	283.2	GREENBELT MD, USA
7109	QUINCY	NOAM	40.0	239.1	QUINCY CA, USA
7110	MON. PEAK	PCFC	32.9	243.6	MT LAGUNA CA USA
7112	PLATTEVILLE	NOAM	40.2	255.3	CO, USA
7114	OWENS VAL.	NOAM	37.2	241.7	O.V. OBS, CA, USA
7121	HUAHINE	PCFC	-16.7	209.0	SOC. ILS., FR. POLYNESIA
7122	MAZATLAN	NOAM	23.3	253.5	SINALOA, MEXICO
7210	LURE, HW	PCFC	20.7	203.7	MAUI, HI, USA
7834	WETTZELL	EURA	49.1	12.9	WETTZELL, FRG
7835	GRASSE	EURA	43.8	6.9	GRASSE, FRANCE
7838	SIMOSATO	EURA	33.6	135.9	HYDROGRAPH. OBS., JAPAN
7839	GRAZ	EURA	47.1	15.5	GRAZ, AUSTRIA
7840	GREENWICH	EURA	50.9	0.4	R.G.O., UNITED KINGDOM
7907	AREQUIPA	SOAM	-16.5	288.5	AREQUIPA, PERU
7939	MATERA	EURA	40.6	16.7	MATERA, ITALY
7943	ORRORAL	AUST	-35.6	149.0	AUSTRALIA

TABLE 2

4+ YEAR GEODESIC BASELINE RATES

Nonweighted Linear Regression: SLR vs. Minster and Jordan (1978)

Baseline Pair Subsets	N	SLOPE	CORRELATION
All possible 4+ yr bslns, (No edit)	134	.854 ± .055	.802
All 4+ yr INTERPLATE bslns, (No edit)	105	.858 ± .054	.840
Baselines, (σ < 40 mm/yr)	131	.850 ± .056	.798
INTERPLATE bslns, (σ < 40 mm/yr)	102	.855 ± .055	.834
Baselines, (σ < 30 mm/yr)	108	.869 ± .060	.814
INTERPLATE bslns, (σ < 30 mm/yr)	79	.883 ± .058	.862
Baselines, (σ < 20 mm/yr)	62	.851 ± .066	.853
INTERPLATE bslns, (σ < 20 mm/yr)	61	.869 ± .056	.864
Baselines, (σ < 15 mm/yr)	68	.889 ± .062	.865
INTERPLATE bslns, (σ < 15 mm/yr)	48	.897 ± .069	.882
Baselines, (σ ≤10 mm/yr)	50	.883 ± .079	.846
INTERPLATE bslns, (σ ≤10 mm/yr)	31	.885 ± .088	.860
Baselines, (σ < 10 mm/yr)	43	.857 ± .088	.829
INTERPLATE bslns, (σ < 10 mm/yr)	31	.859 ± .100	.840
Baselines, (σ < 6 mm/yr)	19	.946 ± .080	.938
INTERPLATE bslns, (σ < 6 mm/yr)	12	.934 ± .090	.948

Table 3

5+ YEAR GEODESIC BASELINE RATES

Nonweighted Linear Regression : SLR v.s. Geologic Models

BASELINE PAIR SUBSETS	N	SLOPE	CORRELATION
5+ YEAR BASELINES ($\sigma < 30$ mm/yr)			
Minster and Jordan (1978) Model Values	50	$0.878 \pm .056$	.912
DeMets NUVEL-1 (1987) Model Values	50	$0.934 \pm .058$	.914
Chase (1978) Model Values	50	$0.858 \pm .056$	.907
5+ YR INTERPLATE BSLNS ($\sigma < 30$ mm/yr)			
Minister and Jordan (1978) Model Values	42	$0.879 \pm .056$	.924
DeMets NUVEL-1 (1987) Model Values	42	$0.935 \pm .059$	.926
Chase (1978) Model Values	42	$0.859 \pm .057$	.918
5+ YEAR BASELINES ($\sigma < 15$ mm/yr)			
Mister and Jordan (1978) Model Values	34	$0.942 \pm .046$	.961
DeMets NUVEL-1 (1987) Model Values	34	$1.005 \pm .046$	.966
Chase (1978) Model Values	34	$0.931 \pm .046$	.961
5+ YR INTERPLATE BSLNS ($\sigma < 15$ mm/yr)			
Minister and Jordan (1978) Model Values	28	$0.942 \pm .041$	.974
DeMets NUVEL-1 (1987) Model Values	28	$1.005 \pm .040$	.979
Chase (1978) Model Values	28	$0.931 \pm .041$	.973

Table 4

Agreement between SLR rates and geologic rates for individual stations

Station	Mean of Ratios	Standard Dev. of Ratios	Number of Baselines
Owens Valley	2.79	4.33	10
Grasse	2.43	4.21	11
Huahine	2.36	2.42	13
Monument Peak	2.22	2.85	15
Quincy	2.07	2.22	18
Otay Mt.	1.82	1.96	8
Bear Lake	1.65	1.46	6
Simosato	1.57	1.34	14
Mazatlan	1.49	1.33	13
Platteville	1.40	0.98	7
Fort Davis	1.35	2.71	15
Greenbelt	1.32	1.13	19
Arequipa	1.26	1.02	19
Yarragadee	1.22	1.04	19
Wettzell	1.22	1.10	10
Lure, Hawaii	1.21	0.80	16
Orroral	1.21	1.18	7
Greenwich	0.87	0.63	13
Graz	0.77	0.68	13
Matera	0.62	0.42	13

Table 5

SLR Rates for Quincy

Station	SLR Rate, mm/yr (r)	Model Rate, mm/yr (m)	SE of SLR Rate, mm/yr (s)	|r-m|	$\frac{\|r-m\|}{s}$
Otay Mtn	45	30	5	15	3.0
Bear Lake	29	2	18	27	1.5
Ft. Davis	5	23	4	18	4.5
Yarragadee	7	-9	6	16	2.7
Greenbelt	5	5	2	0	0.0
Monument Peak	28	30	2	2	1.0
Platteville	10	8	10	2	0.2
Mazatlan	5	29	3	24	8.0
Lure	-1	0	4	1	0.2
Wettzell	-8	-19	5	11	2.2
Grasse	-5	-16	11	11	1.0
Graz	-8	-19	5	11	2.2
Greenwich	-8	-17	5	9	1.8
Arequipa	22	27	3	5	1.7
Matera	-16	-18	5	2	0.4
Orroral	-5	3	10	8	0.8

Table 6

Additional Rates from SLR Data

Station	Rate mm/yr	Bearing °E	Error X bearing °E	S_x mm/yr	S_y mm/yr	R
Quincy(a)	22.0	-22.4	-0.1	1.3	1.1	4.5
Quincy(b)	21.4	-31.7	-27.8	4.5	3.6	2.4
Huahine(a)	16.8	-99.8	36.3	2.6	7.4	4.0
Huahine(b)	17.7	-98.1	33.6	1.9	4.3	4.5
Simo.EU(a)	36.7	-66.4	-1.7	2.8	3.1	13.1
Simo.EU(b)	37.7	-66.3	19.6	2.7	3.0	13.9
Simo.NA(a)	23.6	-44.4	-1.7	2.8	3.1	7.7
Simo.NA(b)	24.7	-45.9	35.2	2.4	3.1	7.8
Simo.PH(a)	22.6	-65.7	-1.7	2.8	3.1	4.9
Simo.PH(b)	24.2	-64.6	-20.0	2.9	3.2	6.1

(a) values calculated using format statistical uncertainties of SLR baseline change.

(b) values calculated using constant uncertainties established from difference between SLR rates and model rates.

Table 7

Relative Motion Velocities at Simosato		
Plate Pair	Direction	Speed, mm/yr
Pacific-North America	69.4°W	86
Pacific-Eurasia	72.0°W	98
Pacific-Philippines	75.5°W	93

Figure Captions

Figure 1. Geometry of determination of baseline length change ($d\lambda/dt$) between two stations P1, P2 from the rotation rate $d\alpha/dt$ about the axis of relative rotation OZ.

Figure 2. Relative motion data for Quincy. The lines show the bearings to other SLR Stations. The numbers opposite the lines show unmodelled motion, -ve numbers meaning relative shortening. The numbers in parentheses show formal errors associated with the baseline rates of change.

Figure 3. Additional motion of Quincy measured by SLR data surrounded by a 95% ellipse of confidence. MJ shows the preferred Basin and Range extension of Minster and Jordan (1987) for comparison.

Figure 4. Same as figure 2, but for SLR Station Huahine (French Polynesia)

Figure 5. Additional motion of Huahine measured by SLR data surrounded by a 95% ellipse of confidence.

Figure 6. Same as figure 2 but for SLR Station Simosato considered to be on the Eurasian plate.

Figure 7. Same as figure 5 but for SLR Station Simosato considered to be on the Eurasian plate.

Figure 8. Same as figure 2 but for SLR Station Simosato considered to be on the Philippine plate.

Figure 9. Same as figure 5 but for SLR Station Simosato considered to be on the Philippine plate.

Figure 10. Same as figure 2 but for SLR Station Simosato considered to be on the North American plate.

Figure 11. Same as figure 5 but for SLR Station Simosato considered to be on the North American plate.

FIG 1

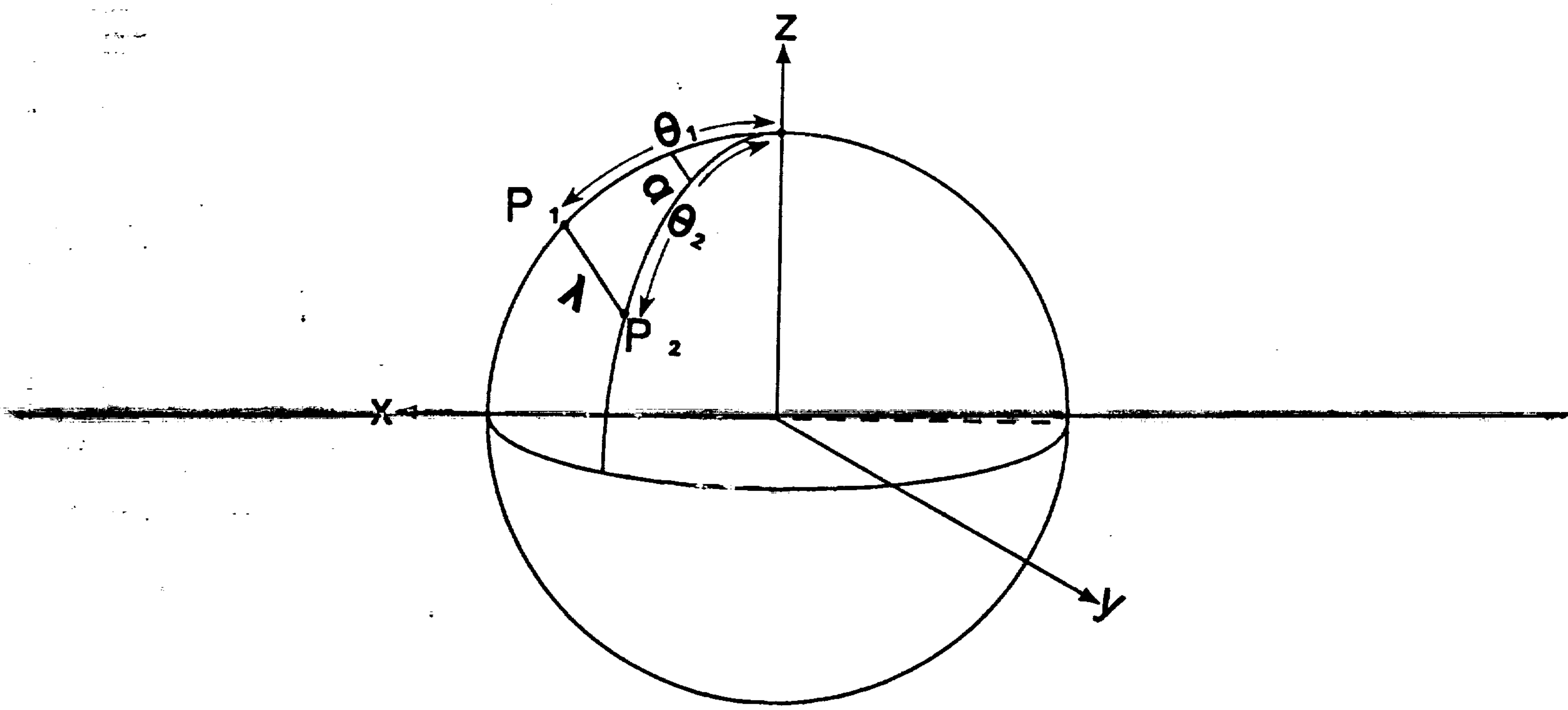

fig 2 Quincy

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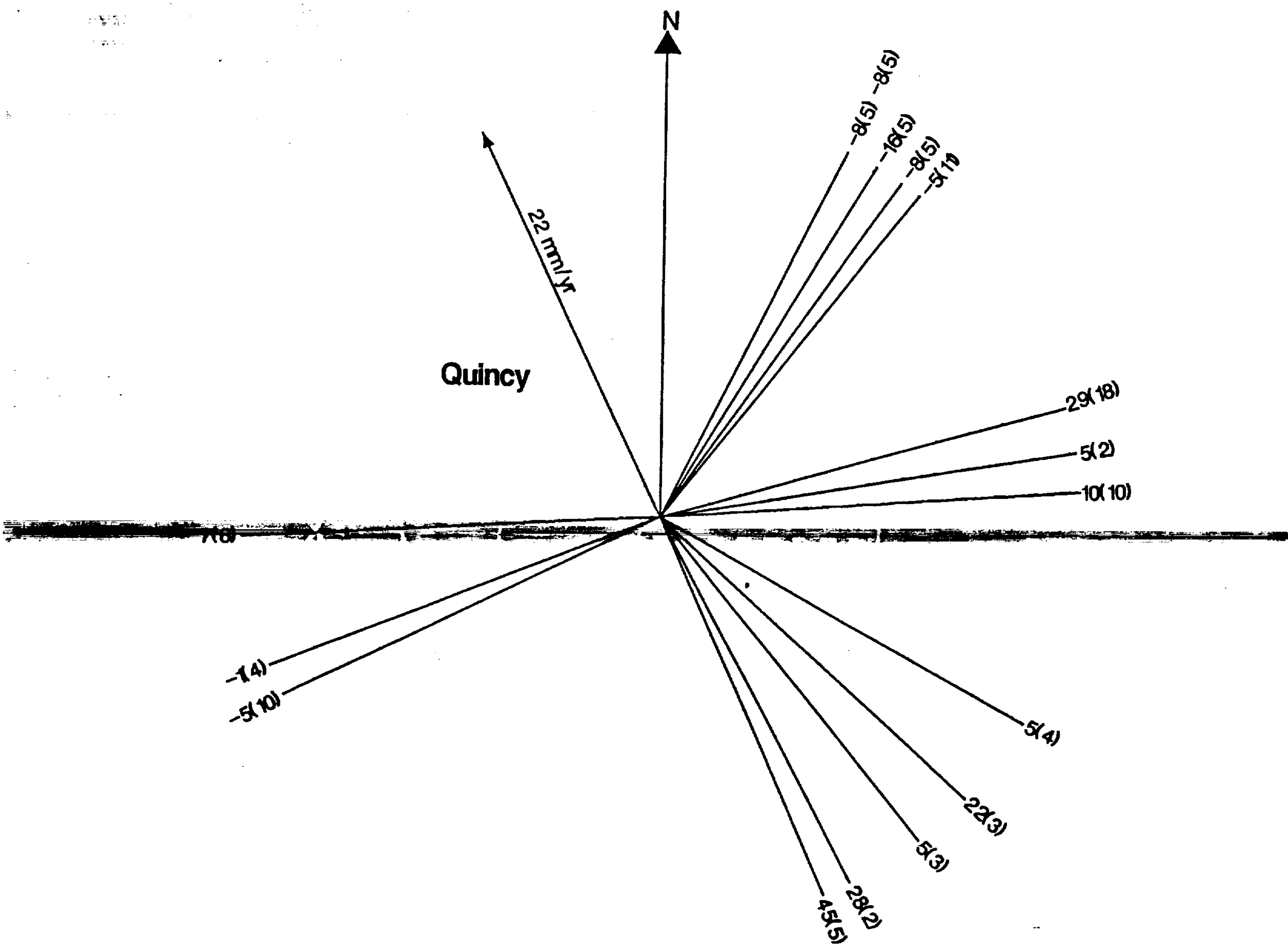
FIG 2



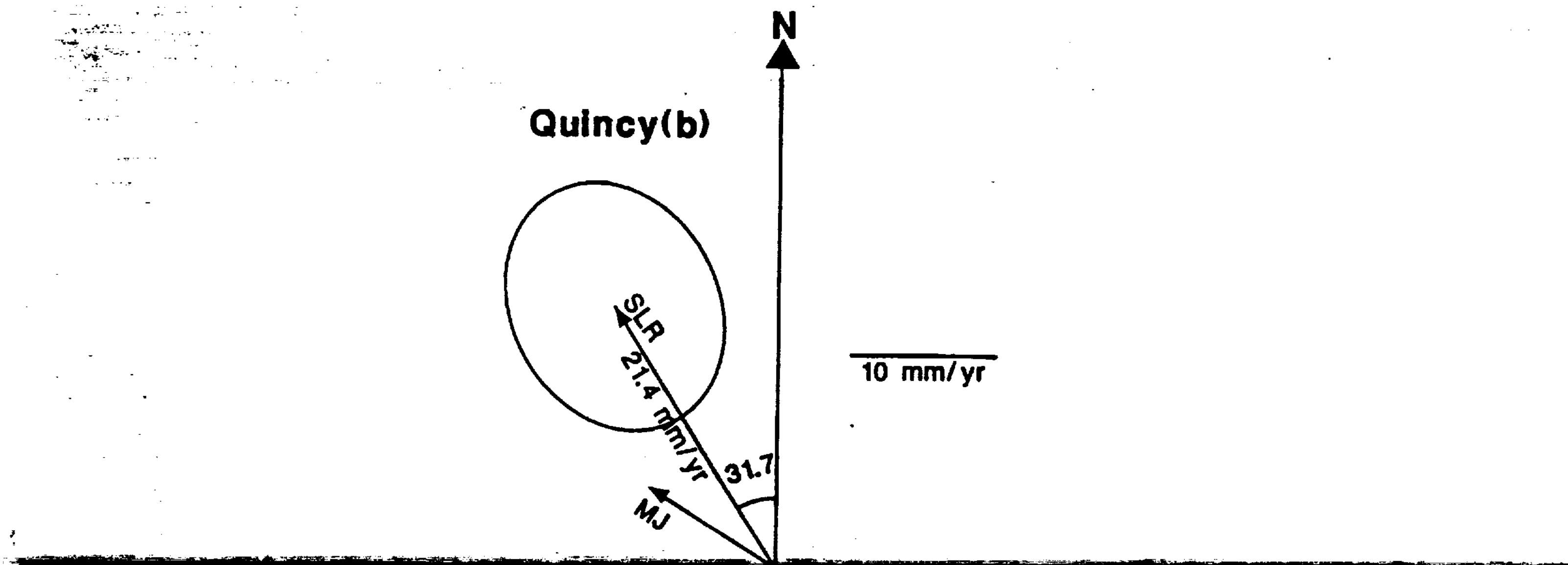

N
Quincy(b)
SLR
21.4 mm/yr
31.7
MJ
10 mm/yr

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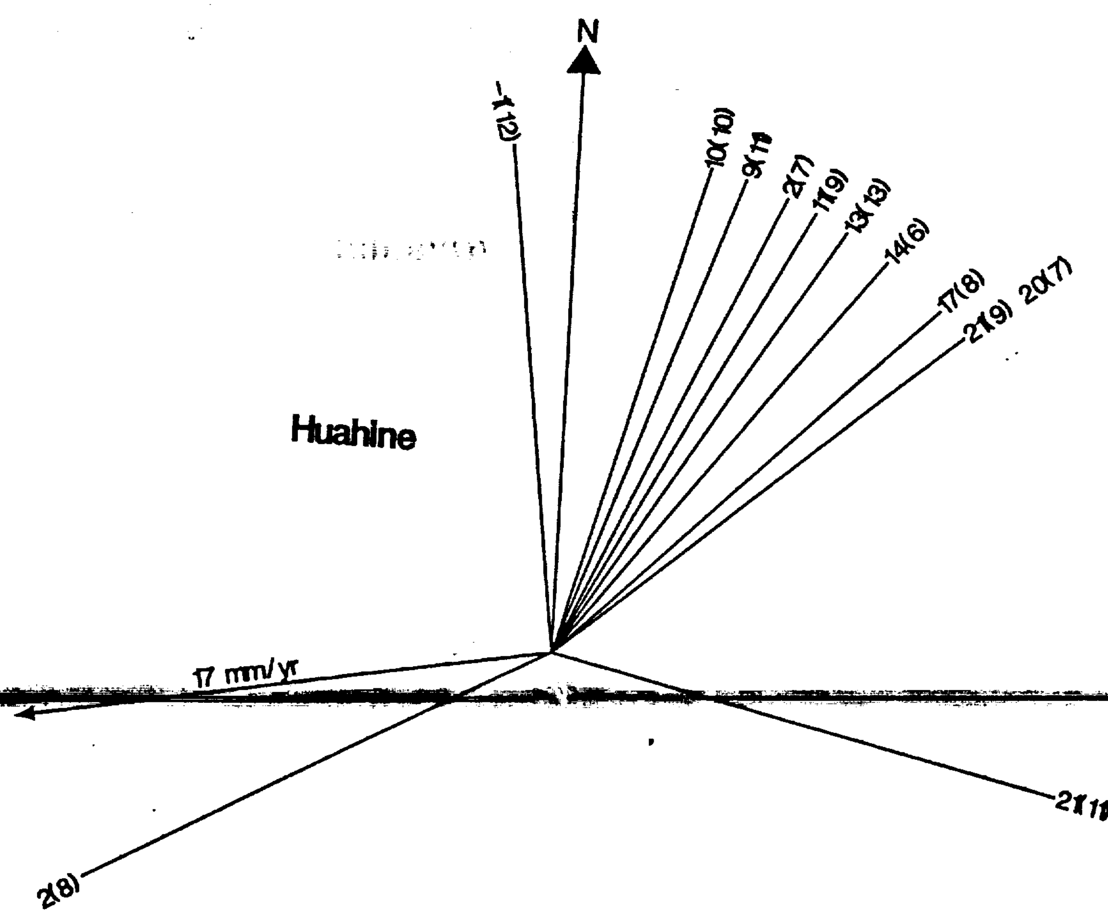
FIG 4



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Huahine (a)

FIG-5

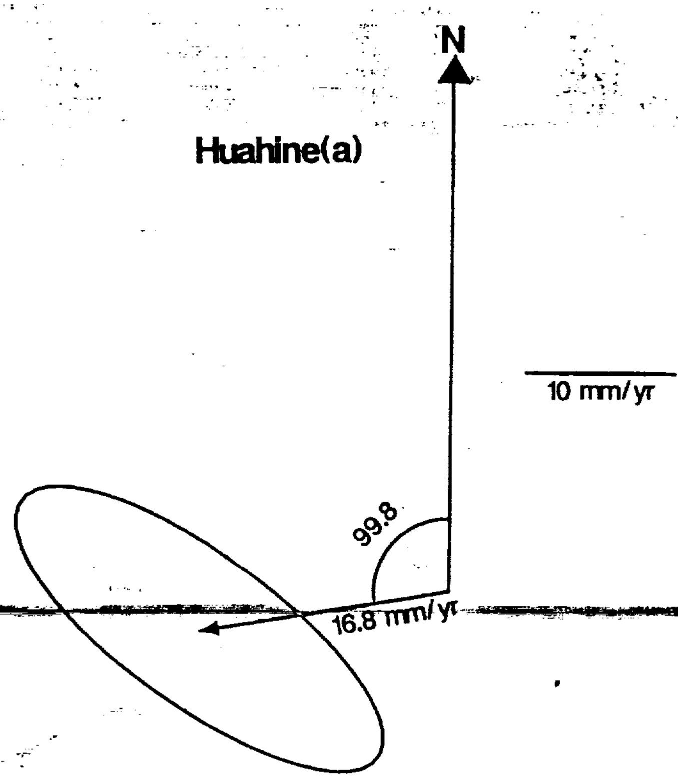

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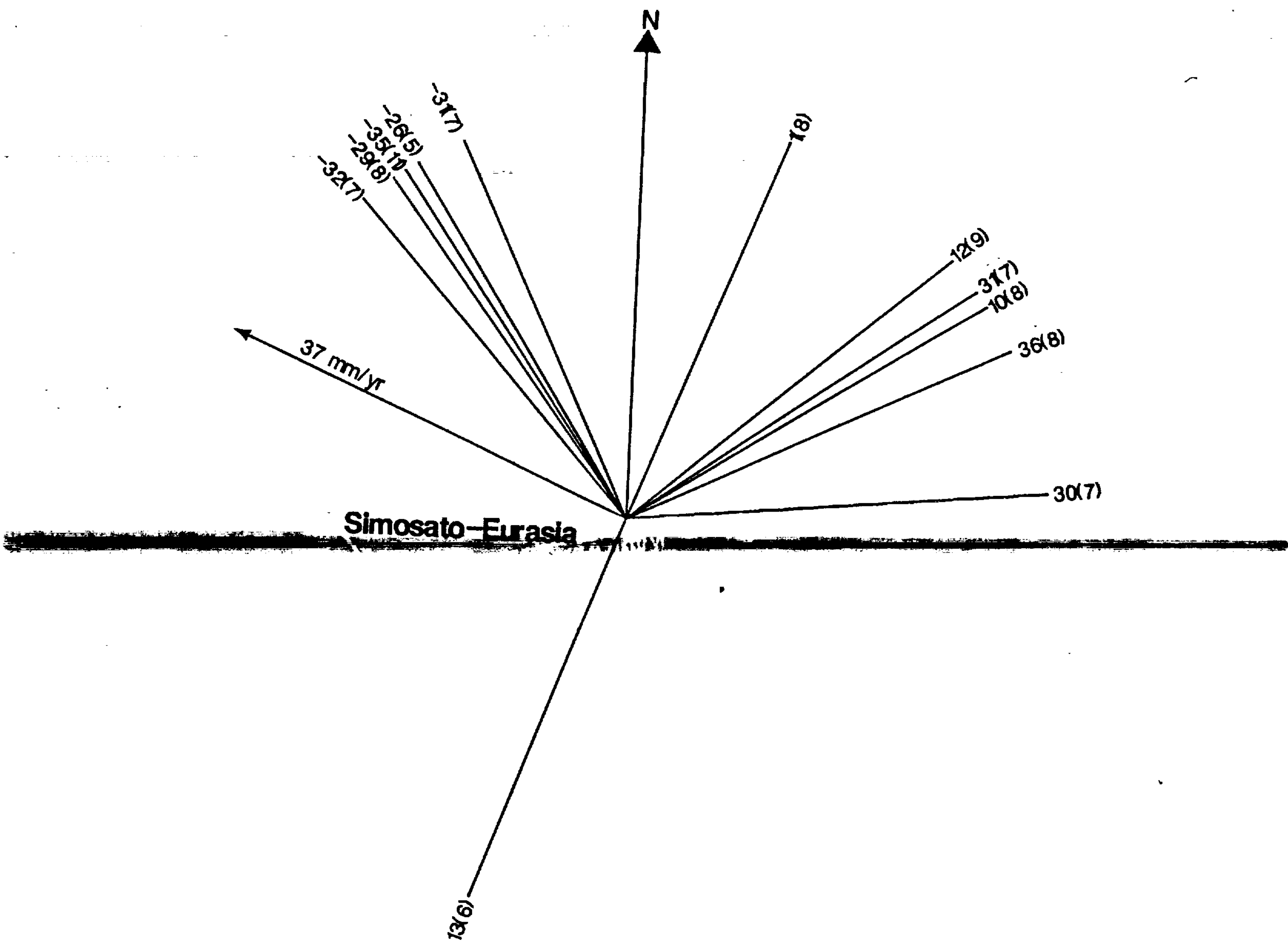
Fig 6 FIG 6

Simosato - Eurasia



Sim. FU (2)

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FIG 7

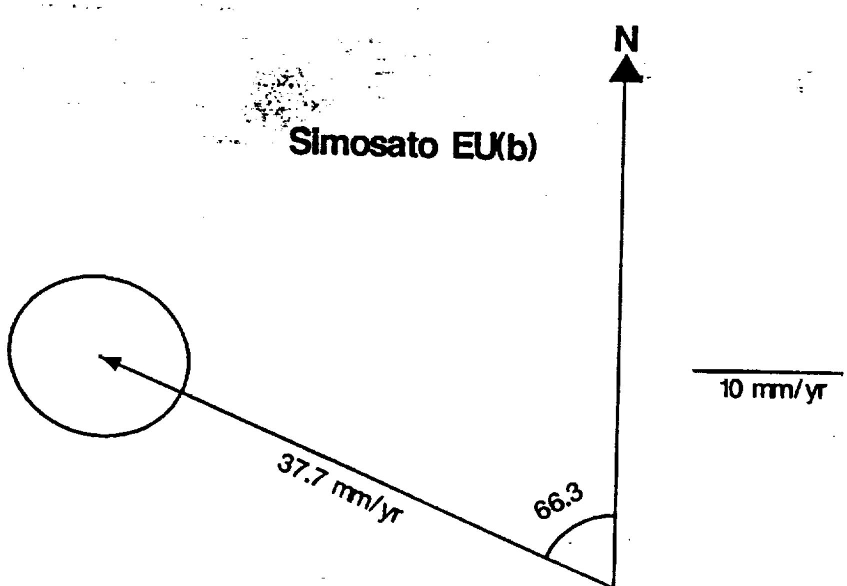

Fig 8 Simosato Philippines

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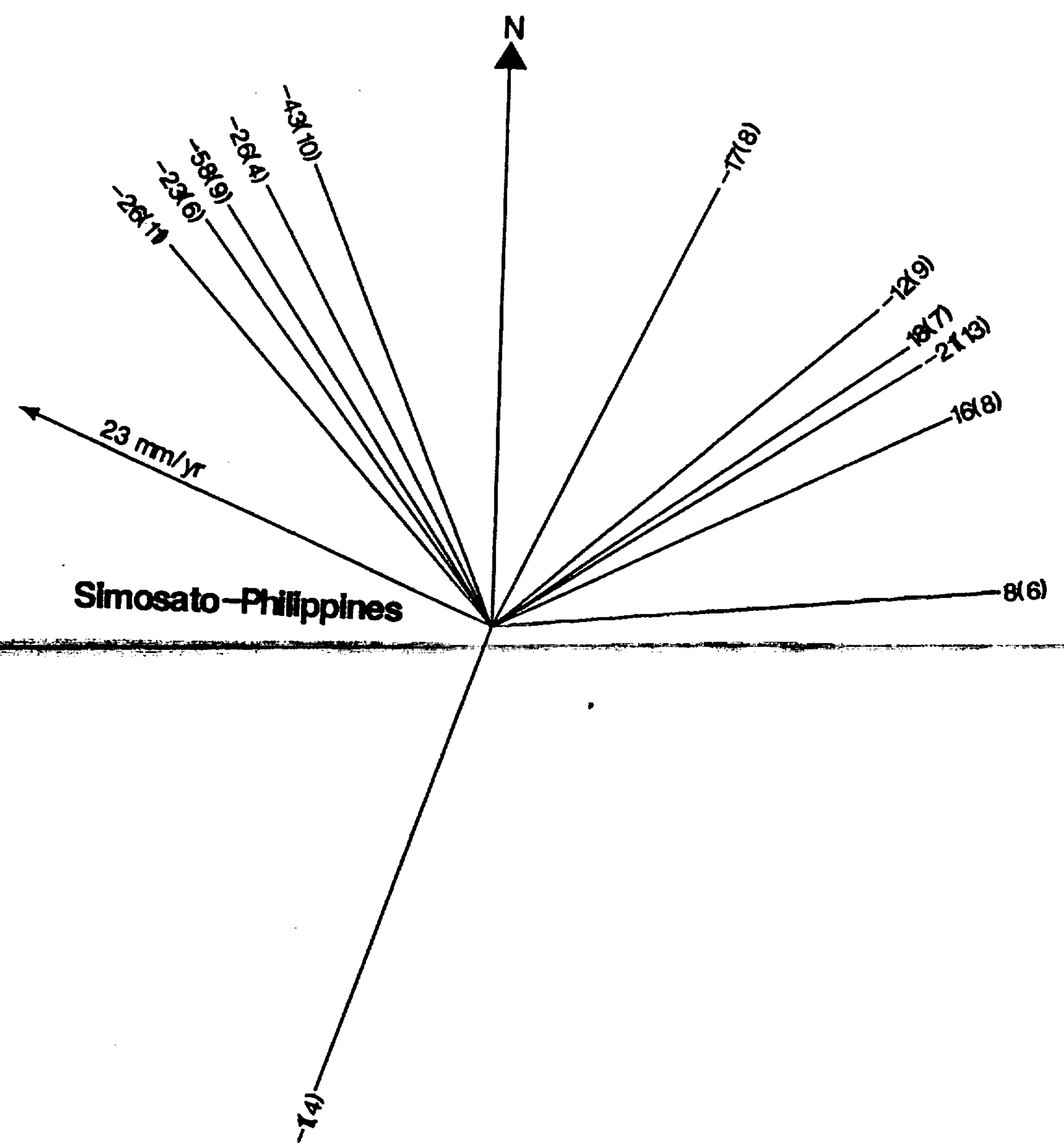
FIG 8



Simo. PH (b)

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FIG 9

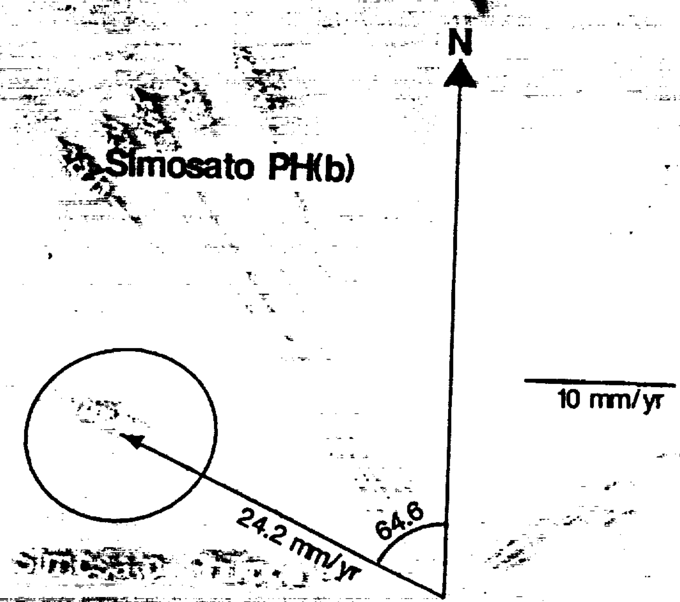

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FIG 10

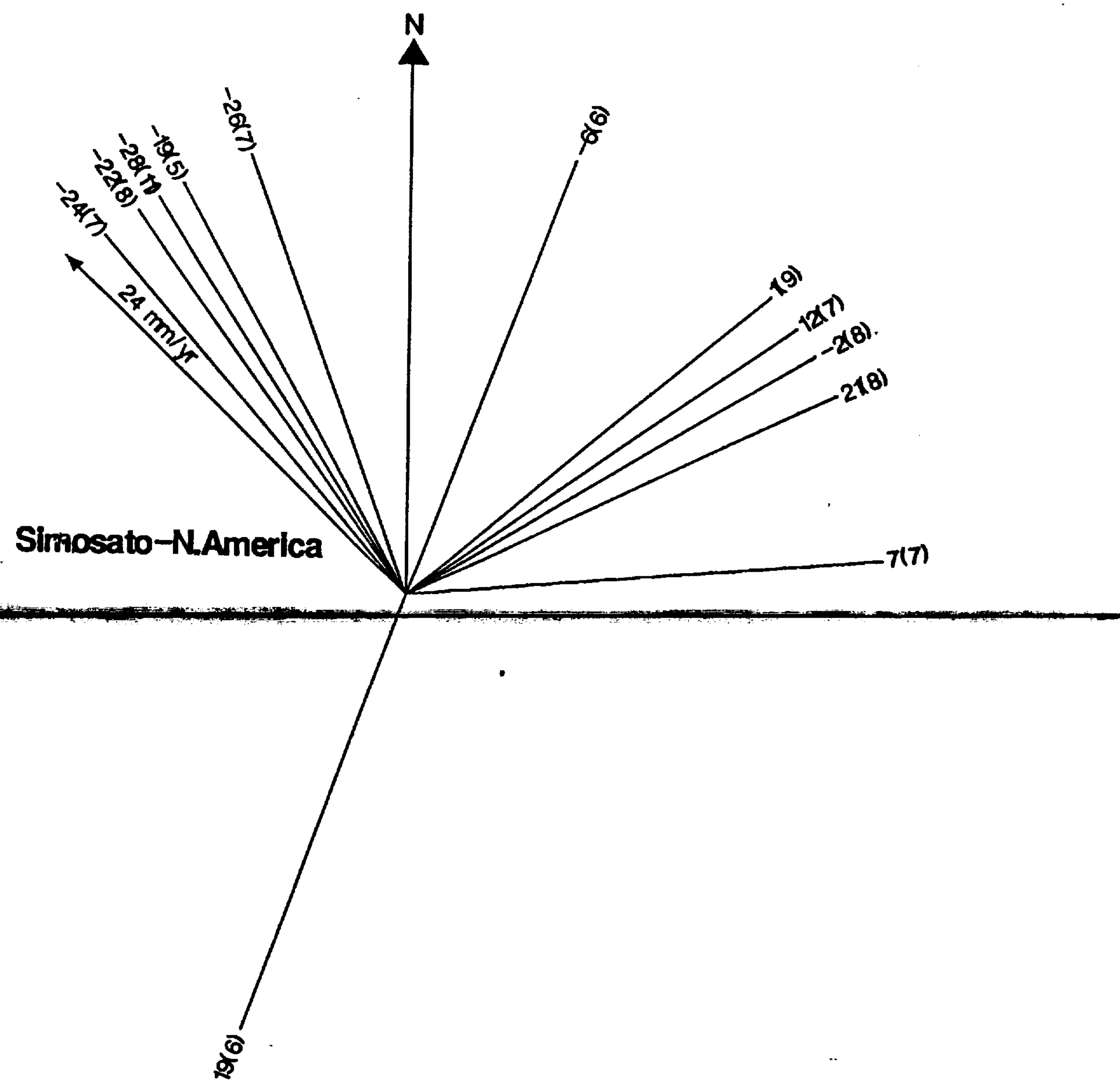
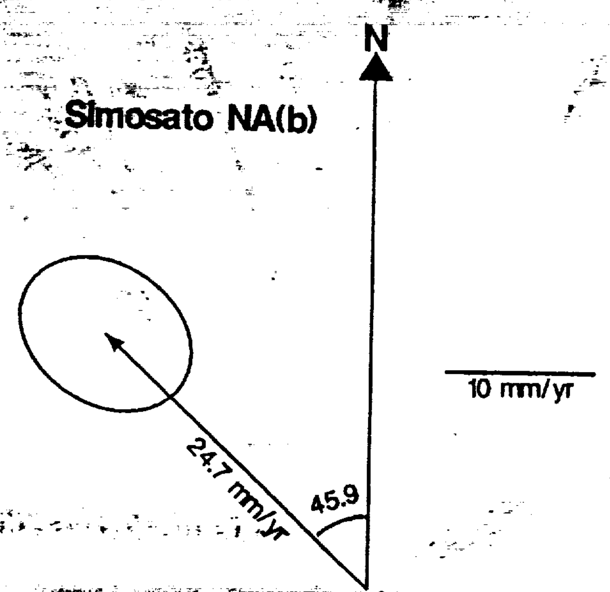


FIG 11



SLR Results and Non-Rigid Plate Motions

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We have analysed Satellite Laser Ranging (SLR) results to the Lageos satellite using data which span a time of 4 or more years, and compared these results with global plate tectonic motions. The SLR data show rates of baseline change between pairs of laser ranging stations. In general there is good agreement between SLR rates of baseline change and those predicted from global plate tectonic motions. However, we have found that for some SLR stations there are significant discrepancies between SLR and plate tectonic data. These will be discussed. One of the main discrepancies is with the data for Quincy, which, lying to the east of the San Andreas fault, is formally on the North American plate. However, the SLR data show that Quincy is participating in strain associated with the Basin and Range and our data agree in general with VLBI and neotectonic data for this region. Data from Simosato in Japan also show discrepancies. In this case, it is not clear on which plate Simosato should be placed, but discrepancies are present for all three possibilities (Eurasia, North America and Philippine). We show that the non-rigid motion of Simosato is explained if its motion is participating in some Pacific motion, in other words, if the strain between the Pacific and other plates is not completely taken up at the trench axis. The reason why this appears likely is that the motion of Simosato not modelled by global plate tectonics is closely aligned with the relative motion vector between the Pacific plate and any of the three plates to the landward. The agreement is best if Simosato is lying on the Eurasian plate, in which case the discrepancy in direction is only 6 degrees. Other data seem to support this hypothesis. In particular, the region behind the arc seems to have a certain number of compressional features. The third station showing discrepancies is Huahine (French Polynesia) but we have no explanation for this, except for non-rigid plate behavior in the Pacific plate, or an unknown plate boundary.

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